Electric Fields in Earth Orbital Space

Final Report

(A002)

May 1989

N00014-80-C-0796

McDonnell Douglas Astronautics Company
Huntington Beach

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Section 1

INTRODUCTION AND BACKGROUND

It has been known for almost a quarter of a century that the extension of the geomagnetic field into space is limited by the flow of the solar wind past the vicinity of the earth. This theoretical prediction was confirmed early in the 1960's by direct satellite observation of both magnetopause and bow shock structures. Several major magnetospheric structures and processes have been discovered since that time. The extended antisolar region of the magnetosphere (the magnetospheric tail) was well documented by the mid-1960's. A cross section of the tail is characterized by a plasma sheet region through the center of the tail (on either side of the magnetic equator). The plasma sheet region separates the northern and southern lobe regions of the tail which are characterized by the relative lack of plasma and bundles of field lines directed toward (in the northern hemisphere) or away (in the southern hemisphere) from the earth. A current system flows through the plasma sheet region and returns at the magnetopause or just beyond it. These crosstail currents are responsible for the lobe structure of the magnetic field and the extended tail topology. In the early 1970's the high latitude magnetosphere was probed with satellites and it was found that there are two cusp regions where the shocked solar wind can penetrate directly to low altitudes. It is believed that a portion of the solar wind plasma directly enters the magnetosphere in these regions. In the mid-1970's further observations of the distant magnetosphere in the magnetopause region showed that a layer of the magnetosheath-like plasma persists just inside of the magnetopause. This boundary layer occurs just inside the magnetopause at almost all locations. The most recently discovered large scale structure in the magnetosphere is the field aligned current system inferred from its magnetic signatures.

All of these magnetospheric features persist at all times. This is not to say that they are steady. Rather, several of them exhibit a wide range of variability. For example, boundary layer thickness at a given location can vary from less than 100 kilometers to over 2000 kilometers. This variability is caused by the magnetosphere's response to changes in the solar wind and interplanetary magnetic field. Clearly, the magnetosphere's response to this variability is an important part in understanding the dynamics of the magnetospheric processes.

In both its ground state and as it responds to changes in solar wind and interplanetary magnetic field, the magnetosphere exerts a profound influence on the near earth orbital environment (the upper atmosphere and the ionosphere). In order to understand and predict this environment (and in some cases to mitigate against its effects) it is necessary to quantitatively understand the structures and processes which persist continuously in the magnetosphere. Studies by the National Academy of Sciences and the National Research Council in the early 1980's have listed the following as critical problems in understanding the magnetosphere:

- How does energy and plasma enter the magnetosphere?
- How is plasma transported within the magnetosphere?
- What are the sources of magnetic and electric fields in the magnetosphere (both their dc and ac components)?
- What are the mechanisms that link the magnetsophere to the earth's upper atmsophere and ionosphere?

Our magnetospheric work at MDAC over the past few years has centered on understanding physically the mechanisms for transfer of energy, mass, and momentum from the magnetosheath region into the magnetosphere, and on describing the interaction of the interplanetary magnetic field (IMF) with the magnetosphere. These are basic problems in magnetospheric physics since these processes must be understood before quantitative models of the many observed magnetospheric processes can be constructed. Such models are required for the prediction and specification of near earth orbital environmental "weather" parameters such as: trapped radiation fluxes, upper atmospheric density, ionospheric electron density, auroral particle precipitation and associated auroral luminosity, etc.

We have developed quantitative models of particle entry and solar wind and IMF influence on the magnetosphere. During this effort for ONR, our attention has been focused on the primary question: Is the substorm controlled by forces external to the magnetosphere or is it primarily a manifestation of processes occurring within the magnetospheric tail region?

Our models are driven by solar wind and IMF parameters. All parts of the models have been developed from first principles. It is our hope that in addition to shedding light on the substorm problem, the models will become useful in the truly predictive sense: that they can be used to anticipate the behavior of several of the routinely observed magnetospheric features and their subsequent effects on the upper atmosphere and ionosphere and the orbital systems that operate in that region.

The solar wind "entry" problem and the substorm have both been important problems in magnetospheric physics since the 1960s. Currently, both problems are explained primarily in terms of "reconnection theory", which we believe has major flaws. We discuss the entry problem first.

1.1 Solar Wind Entry into the Magnetosphere

The first magnetospheric problem to be considered theoretically was the calculation of the size and shape of the magnetosphere. They were determined by equating the solar wind pressure with the energy density (pressure) of the magnetospheric magnetic field. To make this three dimensional problem tractable, an assumption was made; that the solar wind particles were all specularly (mirror like) reflected off of the geomagnetic field, $\underline{B}$. This approximation to the real field was quite reasonable since the interaction region of the incident particles with $\underline{B}$ is very small (10s to 100s of km) compared to the scale size of the magnetospheric magnetic field (10s of thousands of km). This "pressure balance" formalism was used by many investigators to successfully determine the shape and size of the magnetosphere. The unfortunate legacy of this work, however, was the assumption that all of the solar wind particles are reflected off of the geomagnetic field and that none enters the magnetosphere.

Therefore, as early as 1960, concepts were already being suggested for the transfer of momentum across the boundary between interplanetary space (or more precisely, the magnetosheath) and the magnetosphere (the "viscous interaction" theories). Later, as the influence of the IMF on the magnetosphere became well established, the early work of Dungey and others on "reconnection" was suggested as another means for providing energy and mass to the magnetosphere from the solar wind. Several other concepts have been suggested: plasma instabilities along the magnetopause, a structured or "gusty" solar wind, and various diffusion processes.

All this time the assumption that solar wind particles were specularly reflected at the magnetopause was left basically unchallenged. Yet, it was well known that the higher energy solar cosmic rays readily gain access to the magnetosphere. Their entry was explained (correctly) by suggesting that since such particles have relatively large gyroradii, their interaction region with $\underline{B}$ is large enough for them to sample the structure of $\underline{B}$ and therefore possibly gain access to the magnetosphere. (Recall that the path of a charged particle moving in a uniform magnetic field is circular. This fact forms the basis for the specular reflection assumption.)

However, it is known that the strength of $\underline{B}$ along the magnetopause varies from about 75 nT at the nose of the magnetosphere to less than 5 nT in the distant magnetotail. Thus there is a gradient (structure) in $\underline{B}$ (although it is admittedly small over a distance comparable to the gyroradius of a solar wind proton). It was reasonable then to ask: What is the lowest energy particle to gain access to the magnetosphere because of the existence of this known (small) gradient in $\underline{B}$?

We have examined that question in quantitative detail and found that as the energy of the incident particle decreases, the range of directions through which it can enter the magnetosphere also decreases but that even for particles with solar wind energies the solid angle of allowed directions of incidence is finite. Thus, we have concluded that: The assumption of specular reflection may reasonably be used in the determination of magnetospheric size and shape but that some solar wind particles routinely gain access to the magnetosphere.

This work has suggested to us that all the diffusion and plasma instability theories may not be necessary in order to explain the interaction of the magnetosphere and solar wind; that instead all that was necessary was a more realistic examination of the interaction of the solar wind particles with $\underline{B}$.

We have been encouraged by this work since qualitatively it suggests that the solar wind particles will enter the magnetosphere along the sides of the tail and in the dayside cusp regions (where they are required). This contrasts with reconnection theory which suggests that particle entry is primarily at the nose of the magnetopause and over the lobes of the tail. Thus the reconnection theory requires the presence of a complex electric field structure within the magnetosphere in order to allow the entering particles to drift across $\underline{B}$ to the regions where they are observed.

1.2 Problems with the Reconnection Theory

Another basic problem in magnetospheric physics is the understanding of the interaction of the IMF with the magnetosphere. Currently, most of the magnetospheric physics community chooses to represent this interaction in terms of reconnection theory. Basically, reconnection theory supposes that the two magnetic field sources (the IMF and B) become "tied together" in the presence of a plasma. This process has the consequence of connecting the two magnetic fields such that field lines emanating from one are ultimately joined to the other source. An important by-product is the acceleration of charged particles in the "reconnection region". Proponents of reconnection theory suggest that it can explain the entry of the required solar wind plasma into the magnetosphere and also the relatively hot plasma observed in the tail of the magnetosphere.

We have several problems with this theory, however, and with support from ONR have developed an alternative physical description of the IMF and its interaction with the magnetosphere. Some of the problems we see in reconnection theory are as follows. Reconnection is dependent on the direction of the IMF which is observed to change, typically on the order of every few hours. Thus it is not clear to us how any reconnection process can drive any of the processes observed to persist at all times in the magnetosphere (e.g., the plasma sheet, the several magnetospheric currents, etc.). Its proponents state that reconnection takes place predominantly at the nose of the magnetopause and over the lobes of the tail. This poses the requirement of maintaining a complex electrostatic field at all times but in varying directions in order to permit particles entering there to journey to those regions where they are required (e.g., the plasma sheet). Finally, there is no conclusive evidence that this process operates in the IMF and magnetosphere even though a concerted effort has been expended searching for examples. A case in point was the AMPTE ion releases made upstream of the bow shock. No evidence was found for the presence of any ions entering near the nose of the magnetosphere even though the releases were performed during intervals of southward IMF (conditions favorable for dayside reconnection).

Section 2

RECENT ACTIVITIES

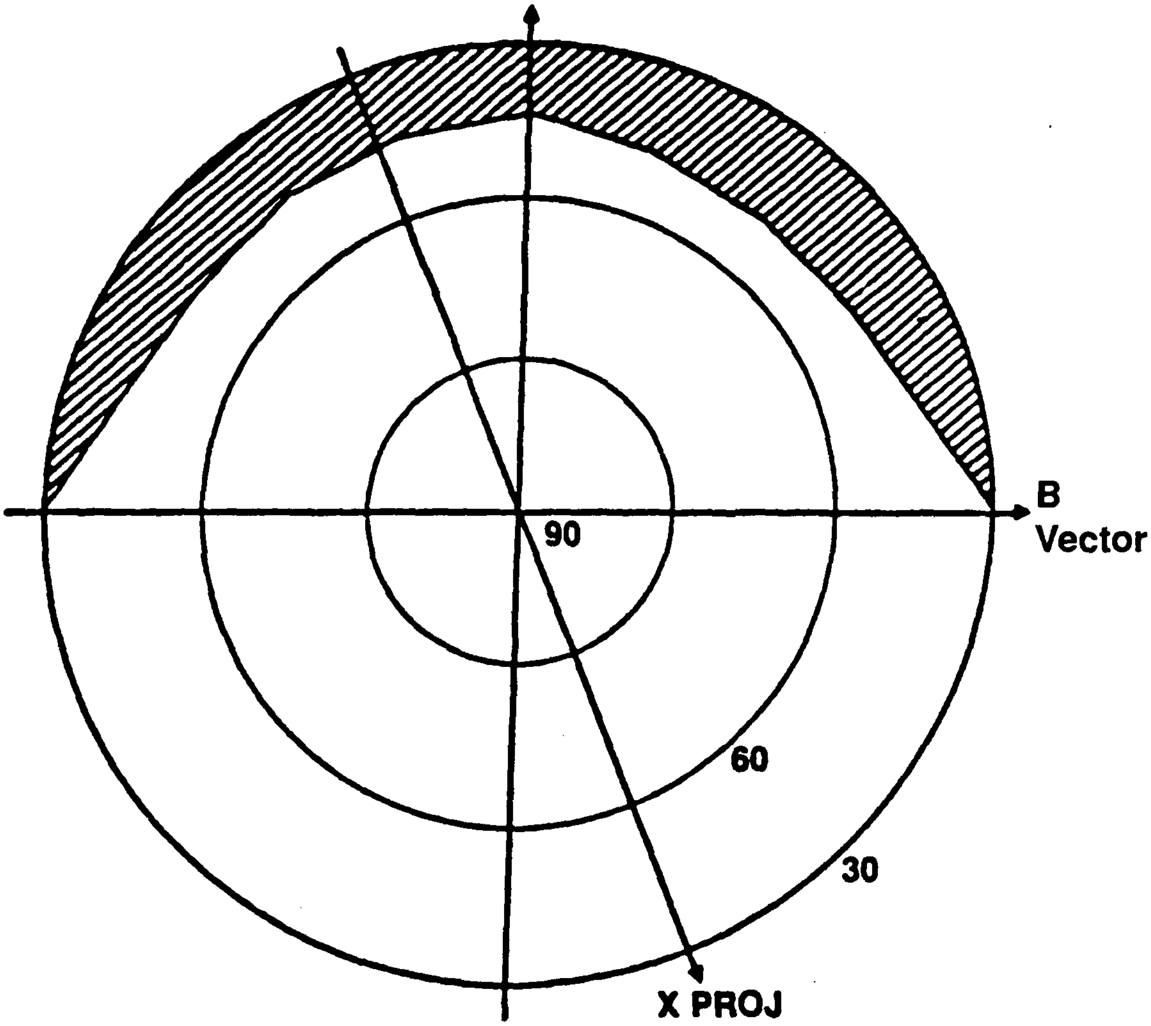
During the last few years we have worked on the entry of solar wind into the magnetosphere and on the control the interplanetary magnetic field (IMF) has on the magnetosphere. Correlative data conclusively prove that both the solar wind and the IMF exert considerable influence on magnetospheric processes, and the magnetospheric substorm in particular.

Our work on this subject may be roughly divided into two parts, particle entry and representation of the interaction of the IMF with the magnetosphere. We discuss particle entry first.

2.1 Particle entry

We have quantitatively determined where on the magnetopause that low energy (solar wind) charged particles can gain entry to the magnetosphere. To do this, we used a realistic quantitative model of the magnetospheric magnetic field. Particles of the same energy but differing incidence angles where then introduced to this field at a point on the magnetopause. It was found that at most points a finite "entry cone" persists. The entry cone is defined as that region (represented as a solid angle) through which particles have access to the magnetosphere. The value of the entry cone varies with particle energy and location on the magnetopause. We found that the entry cone was largest along the equatorial flanks of the tail. (An example of the entry cone is shown in Figure 1 and the size of the entry cone over the flanks of the tail is shown for protons in Figure 2.) The entry cone is exactly zero along the intersection of the noon-midnight meridian with the magnetopause by symmetry since there the particles really are specularly reflected.

Study of entry cone size suggests that no magnetosheath particles enter the magnetosphere over the lobes of the tail and also that no particles enter at the nose of the magnetosphere. The regions where entry does readily occur are along the sides



Bondary Position: -20.00, -17.90, 3.16
1 keV Protons
Entry Cone = 0.249 Sr

Figure 1. Description of an entry cone. The shaded portion represents the range of impact directions over which the particle gains entry to the magnetosphere. The boundary location is down the tail just above the magnetic equatorial plane (along the dawn flank). The projection of the x axis (in solar magnetospheric coordinates) and the direction of B at the entry point are shown. Particles moving away from the sun with a near grazing incidence are shown as "allowed" impact angles.

(flanks) of the tail and in the vicinity of the dayside cusps. The "gradient drift" entry mechanism therefore supplies solar wind plasma directly to those regions of the magnetosphere where plasmas are observed (e.g., the plasma sheet in the tail and the dayside cusps). This is unlike the reconnection theories which introduce plasma near the nose of the magnetosphere and over the lobes of the tail. To date this work on

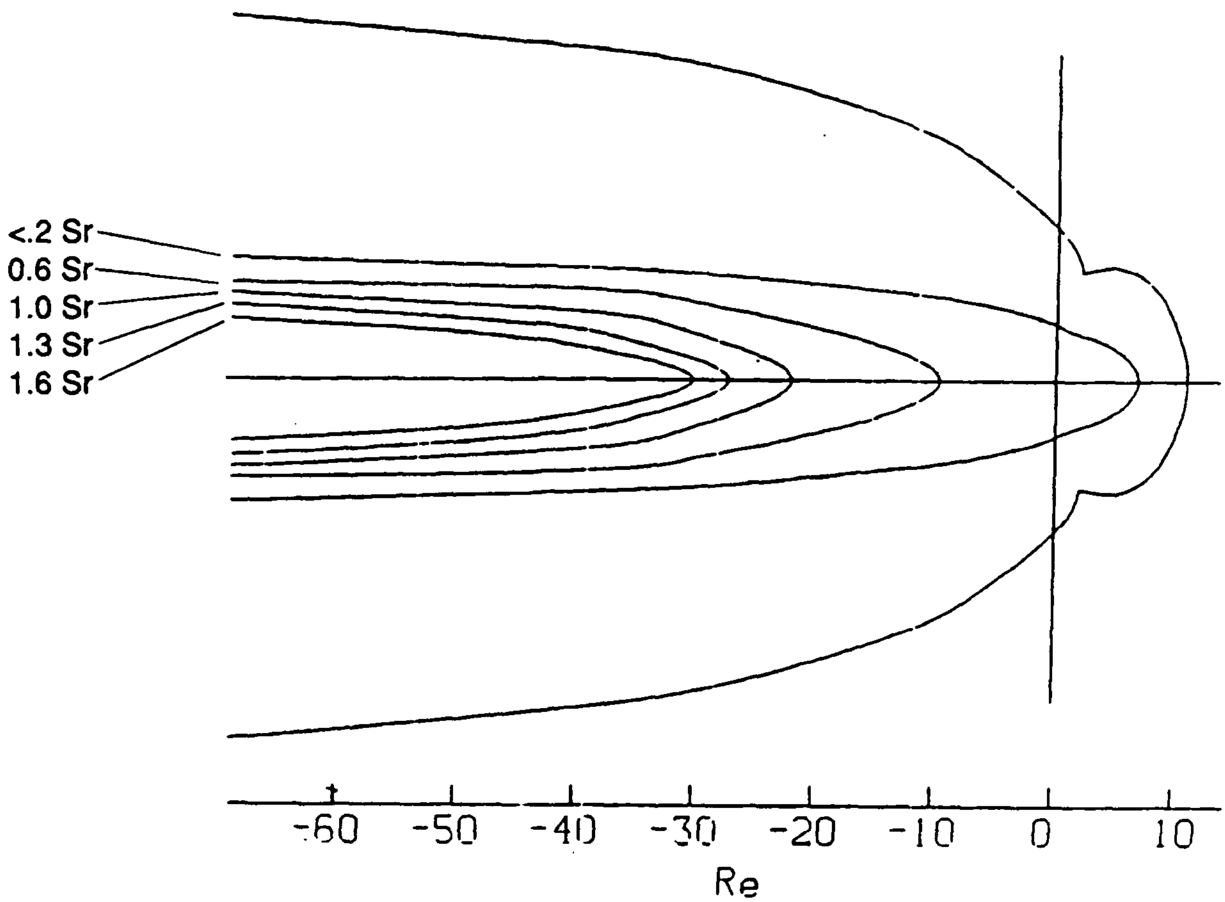


Figure 2. Contours of constant entry cone magnitude on the dawn side of the magnetosphere.

particle entry has shown that particle entry depends on the strength of B, its structure, and on the particle distribution function.

2.2 Representation of the Interplanetary Magnetic Field (IMF)

Correlative data establish beyond doubt that the IMF exerts considerable influence on magnetospheric processes. This subject has been exhaustively studied in terms of reconnection theory. We, however, have several complaints with reconnection theory (it introduces particles into the wrong regions of the magnetosphere: the IMF [and therefore the reconnection process] is continuously changing direction; there is little or no direct magnetospheric observational evidence for its existence etc.); and have, therefore, attempted to explain the interaction of the IMF with the magnetosphere in a way that we can understand the physics.

Basically, we have represented the IMF as the superposition of electromagnetic waves. The only limitation of our investigation is that we must restrict it to wavelengths that are small with respect to the scale size of the magnetosphere. Thus we can examine only waves (or disturbances) with periods less than one hour. Although limited in this regard, our study sheds light on many aspects of the interaction of the IMF with the magnetosphere. These are briefly reviewed. We first summarize our findings on the propagation of electromagnetic disturbances in the solar wind.

The interplanetary field (represented as the superposition of several periodic electromagnetic waves) can persist only in the presence of the solar wind plasma. In the absence of a plasma, the presence of a time varying magnetic field in interplanetary space of the magnitude of only a few nT would have associated with it an electric field with a magnitude on the order of 1 volt per meter, which is at least three orders of magnitude larger than the magnitude of electric fields observed in the interplanetary region.

In the solar wind, in the absence of a background ambient magnetic field, any disturbances with periods on the order of minutes to hours will be rapidly attenuated unless they are driven continuously in a local region. Electromagnetic disturbances in the solar wind can persist only in the presence of an ambient (lower frequency) magnetic field. When such conditions are present (the presence of both plasma and "background" magnetic field) electromagnetic waves with periods from a few minutes to several hours can propagate over distances large with respect to the distance from the Sun to the Earth without appreciable attenuation. The background (ambient) magnetic field is provided by the "solar sector magnetic field" which is co-produced with the solar wind. It moves outward from the sun with the solar wind, and has a period of about two weeks - much longer than the characteristic periods of the electromagnetic disturbances being considered. Electromagnetic waves allowed in the interplanetary medium propagate at the Alfven speed. There are two wave modes that propagate without appreciable attenuation.

1. When the propagation vector is parallel to the ambient magnetic field.

2. When both the propagation vector and the disturbance electric field are perpendicular to the ambient magnetic field direction.

Each of these cases is represented schematically in Figure 3. It then was a simple exercise to examine the interaction of such waves when they encountered a discontinuity in plasma (the magnetopause). At the magnetopause these electromagnetic disturbances are reflected and refracted. A portion of the field can penetrate the magnetosphere. The properties of the penetrating field are determined by magnetospheric parameters (e.g. plasma density, "ambient" magnetospheric magnetic field, etc.). Penetration of these interplanetary magnetic disturbances into the magnetosphere occurs most readily where the magnetic field strength is low and the plasma density relatively high. Thus, the flanks of the tail are the primary region for IMF penetration into the magnetosphere. An example of allowed transmission is shown in Figure 4 where B_0 represents the ambient fields in the magnetospheric and interplanetary regions and B' and E' define the disturbance. Note that the directions of B' and E'

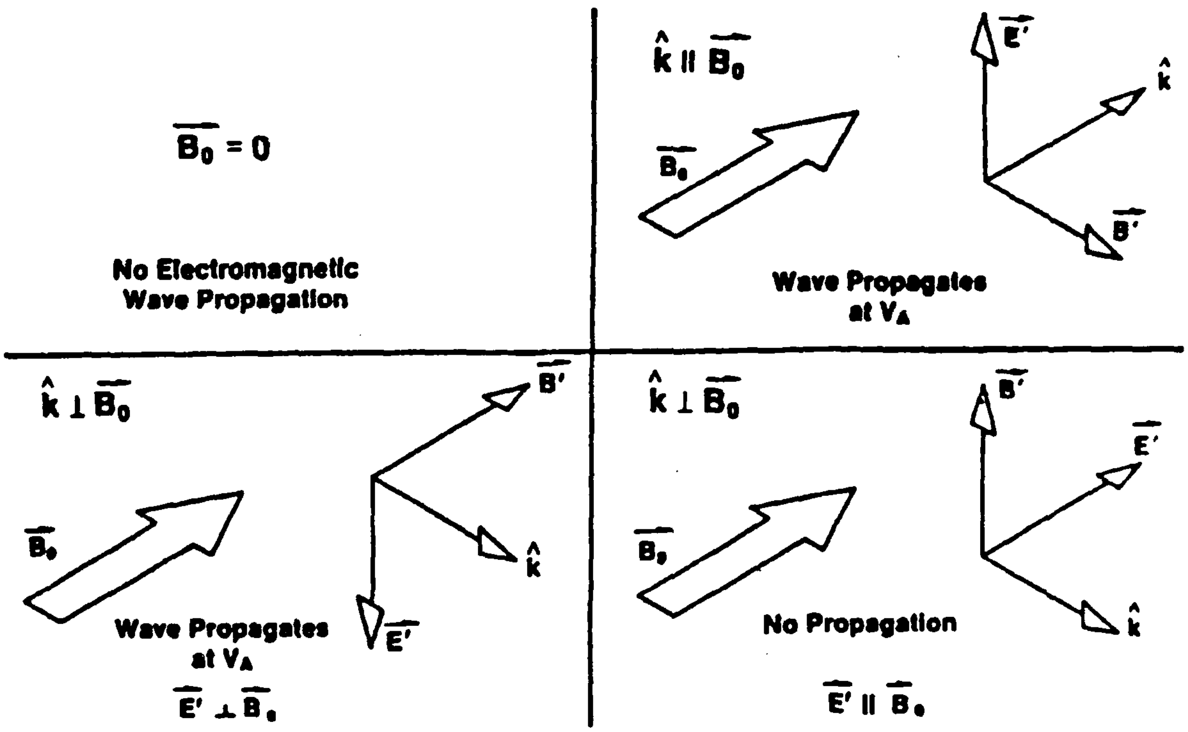


Figure 3. Electromagnetic wave propagation in a tenuous plasma. The wave propagates with little attenuation when its propagation vector is parallel to the direction of the ambient magnetic field, and when the propagation vector and the disturbance $\underline{E}$ vector are perpendicular to $\underline{B}$.

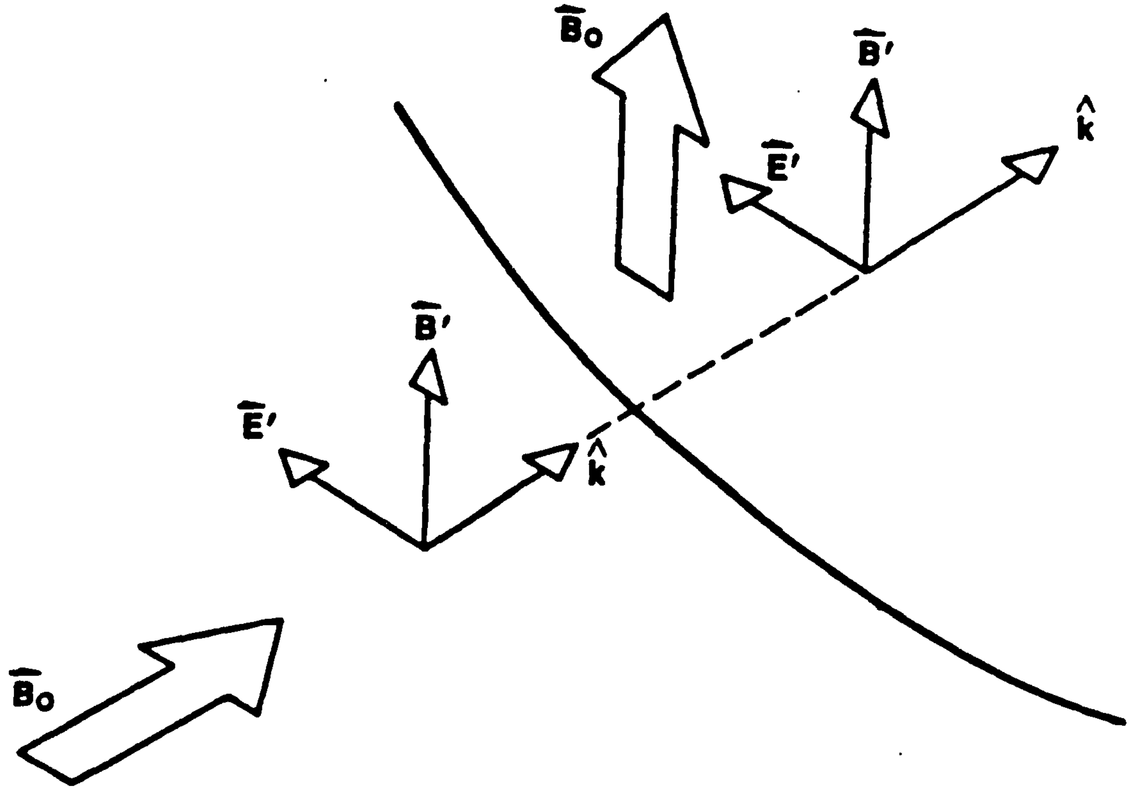


Figure 4. Transmission through the magnetopause and propagation in the magnetosphere. This process is completely analogous to the passage of light from vacuum into glass. In both media (the interplanetary region and in the magnetosphere) the disturbance $\underline{E}$ vector must be perpendicular to the ambient magnetic field direction.

do not immediately change as the disturbance enters the magnetosphere and that E' is always perpendicular to B_o.

Magnetic disturbances in the north or south direction (perpendicular to the magnetic equatorial plane and parallel or antiparallel to the ambient magnetospheric field resident there) can most significantly influence the tail plasma sheet region. The entry of a northward disturbance field decreases the beta (ratio of particle kinetic energy to magnetic field energy density) while a southward field increases beta. We note that for a given ambient magnetospheric field, the entry of a southward disturbance field has more effect than that of a northward disturbance of the same magnitude on the percent change in beta. Thus this work on a physical representation of the IMF has already suggested why a southward directed IMF is observed to have such a large influence on the magnetospheric substorm process.

Section 3

SUMMARY OF WORK PERFORMED

The basic problem of magnetospheric physics remains the explanation of the response of the magnetosphere to variations in the solar wind and the IMF. The work that has been completed places us in a position to take a large step toward the goal of solving that problem. We now understand how the solar wind enters (and influences) the magnetosphere. We have also developed a physical description for the interaction of the IMF (represented as the superposition of a set of periodic electromagnetic disturbances) with the magnetosphere, and are studying the dynamics of energization processes in the magnetotail.

In our earlier work for ONR, we have shown that variations in the IMF can be represented as a superposition of a set of periodic electromagnetic disturbances propagating in the magnetized interplanetary plasma, the solar wind. The solar wind is represented as a tenuous plasma with an imbedded magnetic field, the well known solar sector structure magnetic field. Higher frequency waves can propagate in this medium with the Alfven speed if their propagation direction is parallel to the sector structure magnetic field. Such waves can also propagate if the propagation vector is perpendicular to the sector structure magnetic field providing the wave's electric field. The study also determined that when the wave interacts with the magnetopause, the wave is either reflected or transmitted. The study determined that transmission was possible only near the equatorial flanks of the tail and near the cusp regions, regions of weak magnetic field and where the plasma density inside the magnetopause was relatively high. Once the wave has penetrated through the boundary of the magnetosphere, it will either travel at the local Alfven speed or be absorbed. It was determined that only waves whose magnetic field vector oscillates in the north/south direction are capable of propagating in the interplanetary medium, pass through the boundary near the equatorial flanks and then propagate within the magnetospheric tail field region.

Variations in the north south component of the interplanetary field have long been associated with substorm triggers. To begin the study of substorm trigger, studies of the magnetic field variations in the magnetospheric tail in response to changes in the IMF were initiated. The effort has focused on the development of a model of the magnetospheric tail that included an arbitrary north south wave propagating through the tail at the Alfven speed and the evaluation of the extent to which this traveling wave can act as a substorm trigger. A newly revised dynamic magnetic field model was used as the starting point of the study. The new dynamic magnetic field model consists of four separate magnetic field routines, an internal field routine, a magnetopause magnetic field routine, a ring current magnetic field routine, and a tail current magnetic field routine. The model developed for the IMF wave entering the magnetopause and then propagating within the magnetosphere was written as a time dependent routine which was then combined with the other four existing routine to produce a time dependent magnetic field model.

3.1 The IMF Pulse Within the Magnetosphere

In our previous work for ONR we solved Maxwell's equations for waves traveling in a magnetized plasma and showed that northward or southward changes in the IMF are able to enter the magnetosphere along the flanks of the tail. Once the disturbance pulse is within the magnetosphere it propagates down and across the tail at the Alfven speed. The primary effort during this period of performance was the development of a dynamic model of the magnetosphere that included a propagating wave within the magnetosphere. The effort used the equations developed earlier to create a computer model for the magnetospheric tail that includes the effects of a variation in the IMF.

The computer model of the disturbance pulse developed during this effort begins with a disturbance pulse in the IMF. The disturbance pulse model that has been developed includes the following options:

1. The IMF disturbance can either be north or south (small dawn dusk variations were also modeled).

2. The rise time of the disturbance vector is adjustable. The shape of the rising edge of the disturbance vector was assumed to have a sinusoidal shape (quarter period) of arbitrary duration.

3. The duration of the pulse is adjustable. If the pulse has a finite length, the fall time of the pulse is adjustable. The falling portion of the pulse is also a quarter of a sinusoid.

A specified disturbance having a profile determined by the above constraints is initiated outside the magnetosphere and then allowed to interact with the magnetopause. The wave which enters the magnetosphere near the equator and along the flanks is then allowed to modify the magnetospheric magnetic field.

Five distinct disturbances were modeled, they are:

1. A 4 nanotesla northward disturbance with a rise time of 5 R_e and an infinite pulse length.

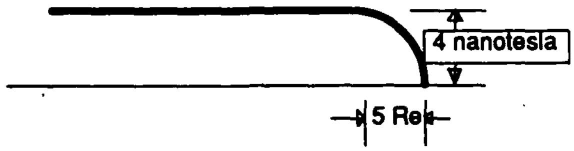
2. A 4 nanotesla northward disturbance with a rise time of 5 R_e and a fall time of 5 R_e.

3. A 4 nanotesla southward disturbance with a rise time of 5 R_e and an infinite pulse length.

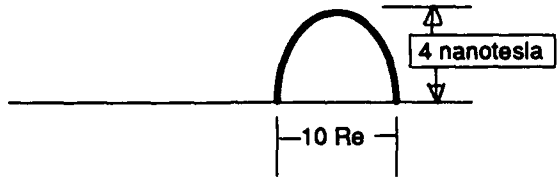
4. A 4 nanotesla southward disturbance with a rise time of 5 R_e and a fall time of 5 R_e.

5. A 4 nanotesla shouthward disturbance with a rise time of 5 R_e and a fall time of 5 R_e having a 1.0 nanotesla dawn dusk variation. Two cases were examined, the first considers propagation in the anti-solar direction, the second propagation along the garden hose angle.

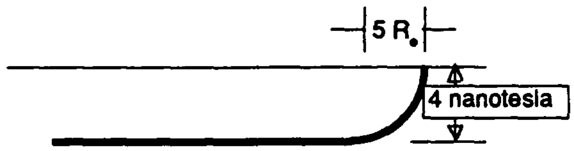
Figure 5 shows the space profile of the north south variation in the IMF. Since the pulse is traveling through the IMF with the Alfven speed, the pulse has definite spatial extent. When the leading edge of the pulse is at a given location, the pulse maximum is some distance upstream. For presentation purposes it is easiest to display the figures as a function of location with each figure describing the magnetic field topology at a fixed time. The pulses used for these test cases were assumed to have their propagation vectors in the ecliptic plane and make a 45 degree angle (approximately along the garden hose angle) with the sun-earth line. The effect of these disturbance pulses on the magnetospheric magnetic field is shown by displaying the behavior of the magnetic lines of force in the noon-midnight meridian plane.



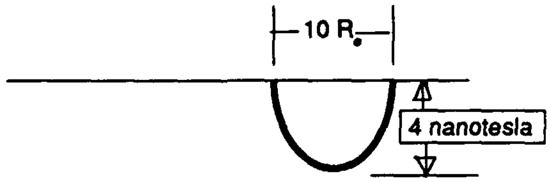
4 nanotesla northward pulse rising to peak value over a distance of 5 R_e



4 nanotesla northward pulse rising to its peak value in a distance of 5 R_e and then decaying agin to zero



4 nanotesla southward pulse rising to peak value over a distance of 5 R_e



4 nanotesla northward pulse rising to its peak value in a distance of 5 R_e and then decaying agin to zero

Figure 5. The above four schematics show the disturbance pulses. The tail magnetic field model was subjected to the four types of disturbances shown above. The pulse moves from left to right at the Alfven speed.

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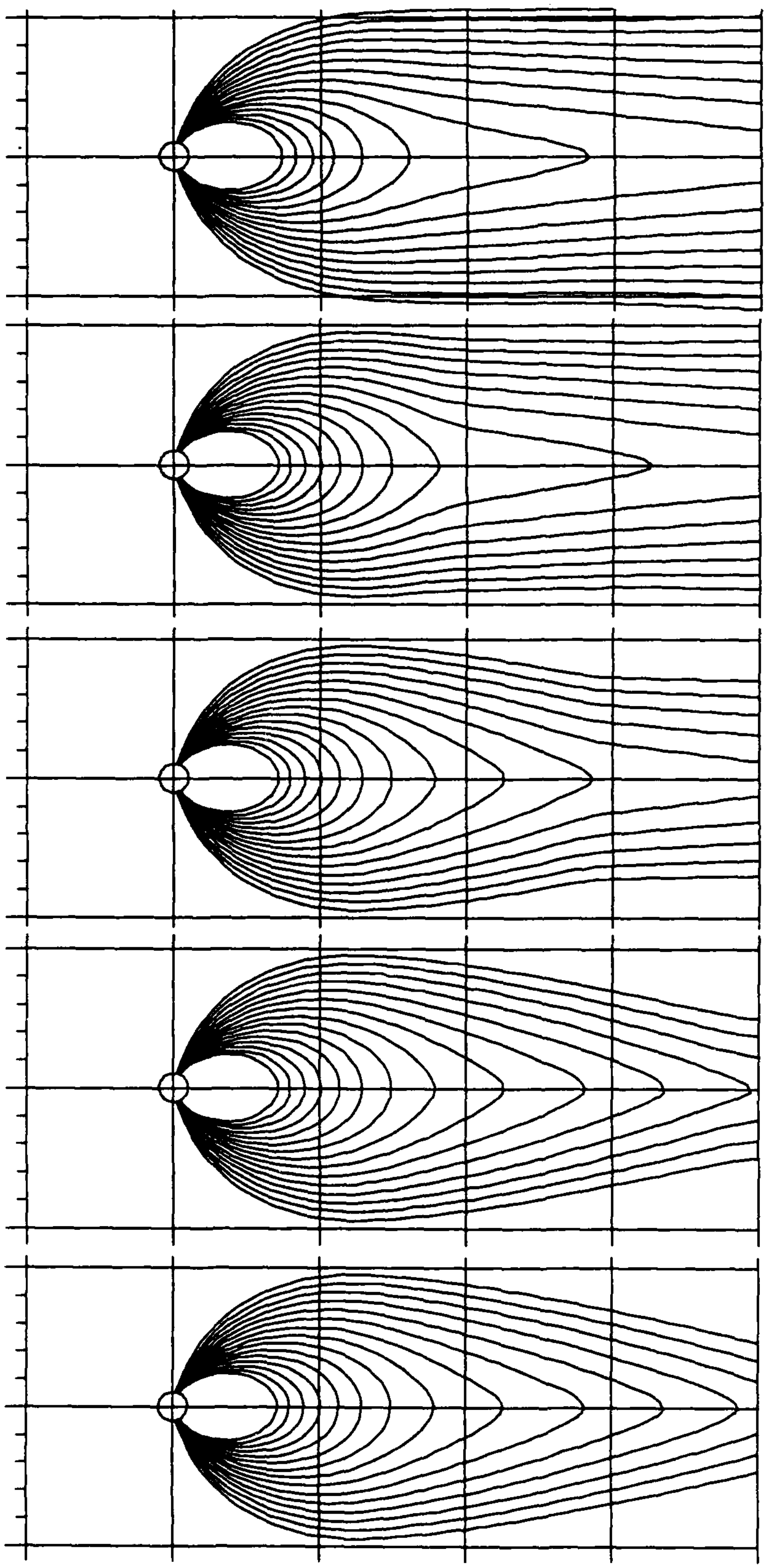
3.1.1 Northward Pointing Disturbance

Figure 6 shows the magnetic lines of force within the magnetospheric tail in the noon-midnight meridian plane. The field lines are spaced one degree apart in the high latitude intercept of the earth. They vary in latitude from 60 degrees to 75 degrees. The top panel is the quiet time magnetic field with only the magnetopause, ring and tail currents contributing to the magnetic field. A northward pointing disturbance of 4 nanotesla having a rise time of 5 R_e and long persistence is allowed to interact with the magnetosphere. The second panel shows the magnetic field topology when the leading edge of the disturbance pulse has reached the -20 R_e. The remaining panels show the changes in the magnetic field topology as the pulse propagates down the tail. The northward disturbance strengthens the z-component of the magnetic field in the tail and thus produces a more dipolar tail field geometry. When a short northward disturbance is allowed to propagate down the tail, the results are very similar to the above result with the long pulse. The field becomes more dipolar in a limited region of space. Once the pulse has passed, the field recovers to its initial configuration.

The increasing tail strength due to the entering disturbance wave has many interesting implications. The long pulse reduces the magnetic field gradients along the flanks of the tail and thus reduces the amount of magnetosheath plasma that can enter across the magnetospheric boundary. The enhanced field within the tail increases the magnetic current limit, and thus increases the allowed plasma sheet current densities. Thus the electric field strength in the boundary layer as well as the cross tail electric field must change in response to these variations in the magnetic field and magnetic field gradients. The effect of these changes on the plasma and on the electric fields have not yet been determined.

3.1.2 Southward Pointing Disturbance

Figure 7 shows the magnetic field lines in the noon-night meridian plane when a southward disturbance propagates through the magnetosphere. The disturbance pulse rises over a distance of 5 R_e and remains at the disturbance level for an extended time (see figure 5). The top panel represents the quiet magnetosphere before the arrival of the pulse. The next panel shows the tail field topology when the leading edge of the pulse is at -20 R_e. Subsequent panels show the leading edge moving in the anti-solar direction. It can be seen that the pulse results in a weakening of the tail and that the tail takes on a more taillike appearance (i.e. the tail becomes extended). When the



Quiet time - field lines using Magnetopause, Ring and Tail current systems only

Leading edge of disturbance is at -20 R_e

Leading edge of disturbance is at -30 R_e

Leading edge of disturbance is at -40 R_e

Leading edge of disturbance is at -50 R_e. Note: Dipole-like compressed tail.

Figure 6. Noon midnight meridian cross section of the tail showing the propagation of a northward pointing disturbance. Pulse is a long 4 nanotesla northward pulse.

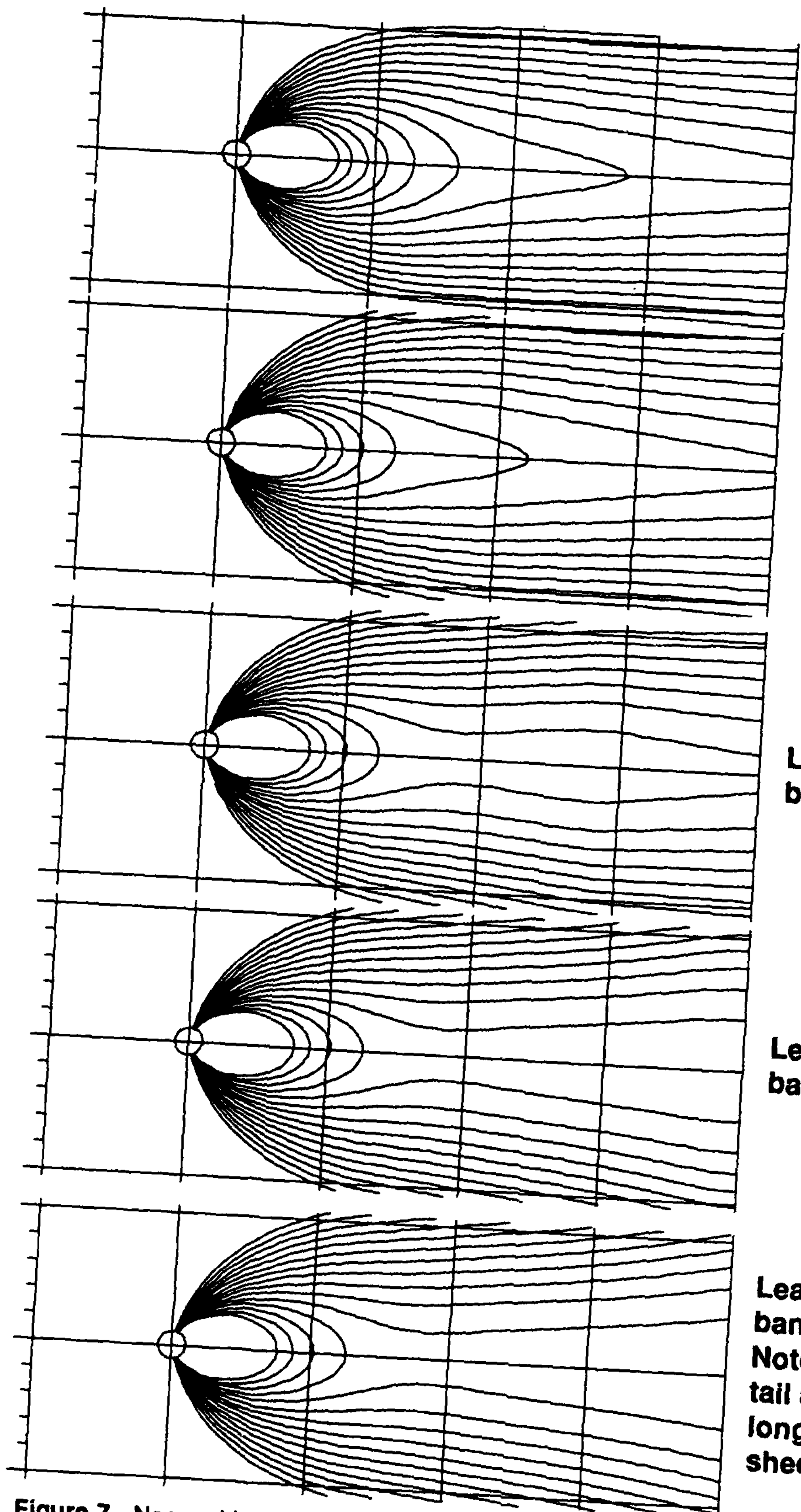


Figure 7. Noon midnight meridian cross section of the tail showing the propagation of a southward pointing disturbance. Pulse is a long 4 nanotesla southward pulse.

pulse is at distances larger than -30 R_e, the figures show a bulge in the field lines near the neutral sheet (i.e. the field lines no longer appear to cross the neutral sheet). To investigate the behavior of the field lines in this case it is necessary to generate a second set of field line plots, a set where all field lines are forced to originate from the equator. Figure 8 shows the same case but in this figure the displayed field lines originate at the equator instead of the polar cap. One can see that pulse creates an "O" and an "X" type neutral point. There is a set of field lines that is no longer connected to the polar cap and this set of field lines moves in the anti-solar direction along with the disturbance pulse. For this long extended pulse the "O" type neutral point moves down the tail, whereas the "X" type neutral point remains fixed near -20 R_e.

Figure 9 is similar to Figure 8 except that the disturbance pulse is short. The pulse rises from 0 to 4 nanotesla in 5 R_e and then decays to zero over a distance of 5 R_e. Once again the top panel is the undisturbed configuration and subsequent panels show the disturbance pulse at different locations in the tail. In this figure both the "X" and "O" type neutral point move down the tail at the speed of the disturbance.

The behavior of the field lines when a southward disturbance is introduced is similar to the "plasmoid" topolgy often described by experimentalist. The southward disturbance significantly weakens the field in the tail neutral sheet. It actually reverses the field over a region of the neutral sheet and thus produces the neutral points. The weakening of the field reduces the amount of plasma the field can support and the magnetically limited currents are drastically reduced. This analysis is a first step and includes only the first order effects of the propagating magnetic wave. It does not as yet include the effects of the plasma response. The plasma response is expected to significantly alter the behavior of the pulse because the beta of the plasma near the neutral point will exceed one unless the plasma rearranges itself in response to the magnetic field.

3.1.3 Southward Pointing Disturbance Accompanied by a Dawn Dusk Variation.

A wave travelling in the IMF along the garden hose field line can have variations in the ecliptic plane as well as variations perpendicular to it. The previous examples consisted only of waves having magnetic variations perpendicular to the ecliptic plane. We now consider a wave that has the same variation perpendicular to the

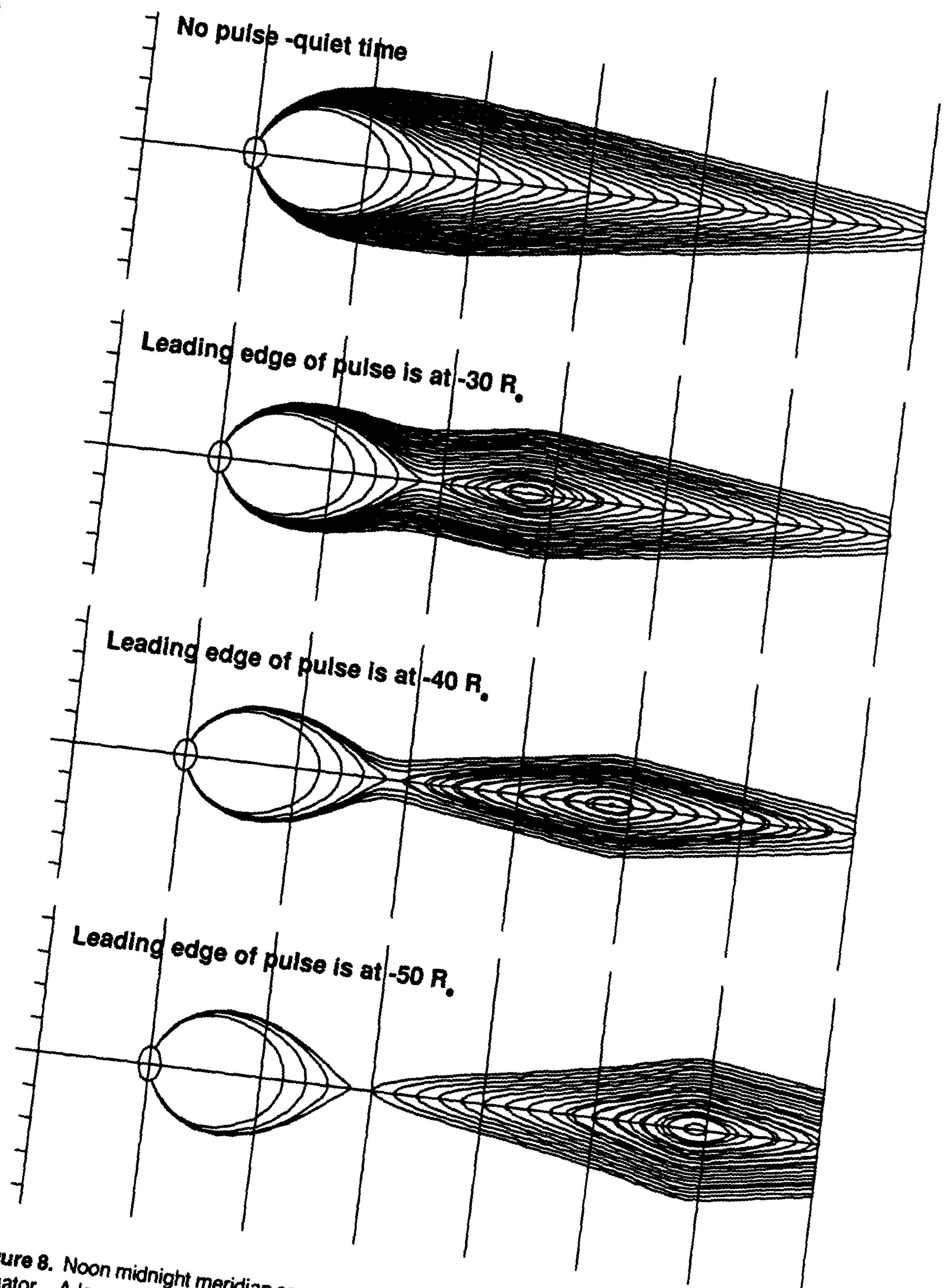


Figure 8. Noon midnight meridian cross section of the magnetosphere. Field lines are drawn from the equator. A long 4 nanotesla pulse moves down the tail. Note the 'X' and 'O' type neutral points.

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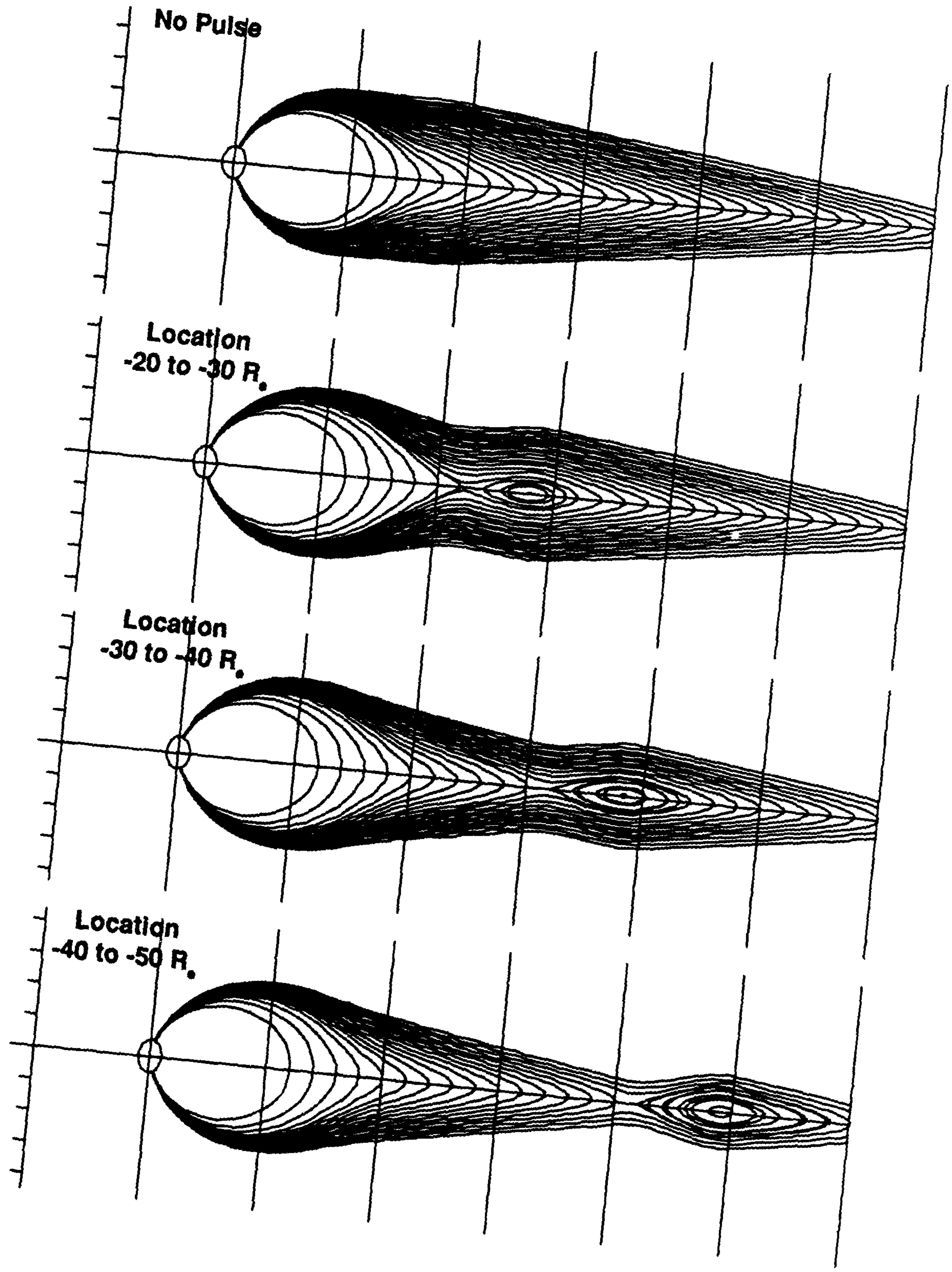

Figure 9. Noon midnight meridian cross section of the magnetosphere. Field lines are drawn from the equator. A short 4 nanotesla pulse moves down the tail. Note the 'X' and 'O' type neutral points. The distrubance pulse rises in a distance of 5 R_e and than decays back to zero in a distance of 5 R_e.

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ecliptic plane and also has a magnetic variation in the ecliptic plane. This wave has the same propagation properties in the IMF as the previous waves and the interaction at the magnetopause is the same. However, when this wave enters into the magnetosphere parts of the wave are damped. The dawn dusk component of the wave has an electric field vector perpendicular to the equatorial plane and thus the dawn dusk component is damped in the center of the plasma sheet. Near the edges of the plasma sheet, the dawn dusk variation can, however, propagate through the tail. Figure 10 is a 3-dimensionally picture of a field line in the plasma sheet when the disturbance containing both north south and dawn dusk variations is propagating in the anti-solar direction. The superposition of the field from the IMF with the magnetic field of the magnetosphere gives rise to a spiral field line topology. Such spiral field line topologies have been postulated by experimentalists and are often referred to as 'flux ropes'.

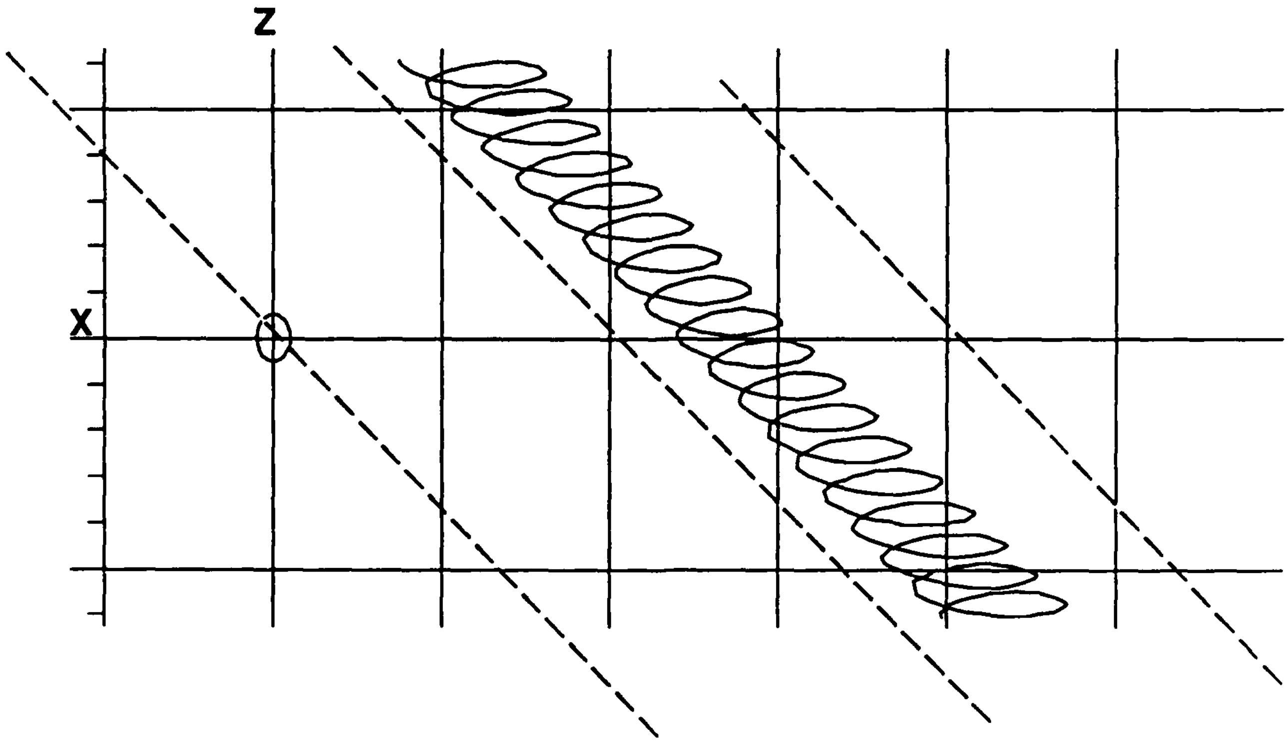

Figure 10. A 4 nanotesla southward IMF pulse with a 1 nanotesla dawn dusk component. Pulse is travelling in the anti-solar direction. The 'Flux Rope' lies in the equatorial plane extending accross tail in the Y direction.

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Figure 11 shows a field line in the plasma sheet when the north south and dawn dusk disturbance propagates across the tail at a 45 degree angle. The wave enters on the dusk side and propagates down the tail and moves from dusk to dawn. The spiral field line topology has developed in only a portion of the plasma sheet. The ends of this spiral connect to either the ionosphere or the distant tail. The example in Figure 11 shows a connection to the ionosphere.

The examples in Figures 10 and 11 demonstrate the simplicity of creating very complex structures within the magnetotail, structures that have been experimentally observed on numerous occasions. Many complex theories have been created to explain the existence of these structures. This study, however, suggests that a simple interaction between the magnetic variations in the IMF and the magnetospheric magnetic fields can also be used to explain the observations.

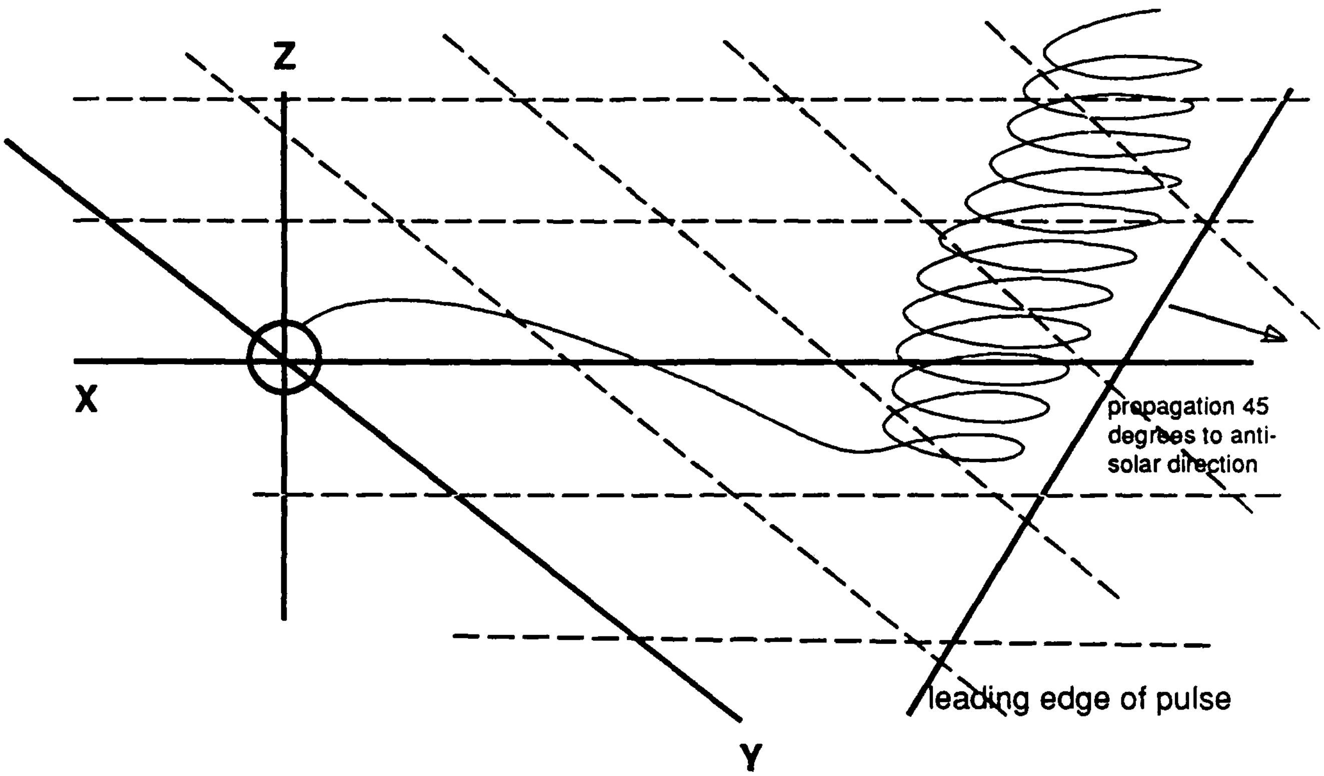

Figure 11. A 4 nanotesla southward pulse with a 1 nanotesla dawn dusk component propagating through the plasma sheet. The propagation direction is 45 degrees to the x-axis. The 'Flux Rope' lies in equatorial plane and extends part way acros the tail with the field line teminating in the iono-

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3.2 Summary of Work

The models of the disturbance wave propagating within the tail of the magnetosphere are the first of a series of steps necessary to develop a comprehensive understanding of magnetotail dynamics. This work in conjunction with the work on particle entry into the magnetosphere will provide a detailed understanding of magnetospheric particle energization. The magnetic field model of the disturbance magnetic field when combined with the existing dynamic magnetic field model provides a tool for evaluating the response of the plasma to the magnetic stimulus of the IMF. This effort will ultimately permit us to understand the role of the IMF in controlling and/or triggering processes within the magnetosphere.

The above described dynamic model of the plasma sheet magnetic field during variations in the IMF can be used to study the response of the tail to external stimuli. Much work needs to be done. The above described model is not self consistent. Although solutions to Maxwells equations were used in arriving at the propagation equations, the response of the local plasma to this traveling wave is not treated self consistently. In the plasma sheet the beta of the plasma is very close to unity. Thus when a southward disturbance weakens and at time even reverses the field in the plasma sheet, the cross tail currents are explosively disrupted with a release of a considerable amount of energy. It is apparent from this study that the changes in the plasma sheet produced by the interaction of the IMF with the magnetospheric magnetic field produces changes that are more than adequate to produce the variation observed during a sub-storm. A complete quantitative model of a sub-storm must include not only these triggering effects but also the response of the plasma sheet plasma to this variation.

The model of the plasma sheet developed under this effort is relatively simple and provides considerable insight into some of the observed variations within the plasma sheet. Many of the complex magnetic field topologies that have been postulated by various experimentalists to explain complex magnetic field and charged particle observations are explained by this analysis.

This effort has laid the ground work for a successful analysis of the data set assembled during the ninth Consolidated Data Analysis Workshop (CDAW-9). Data from this workshop is now assembled in the NASA-GSFC data base and available for use. The results of this study as well as our particle entry work were used to select the events that make up CDAW-9.

Considerable progress has been made in understanding the dynamics of the magnetotail. We have developed a dynamic model of the magnetotail magnetospheric magnetic field. Extensions to this work that take into account the response of the plasma to the external stimuli will help develop a model that can link cause and effect within the entire magnetosphere.

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Section 4

PUBLICATIONS AND PRESENTATIONS

The Contribution of Magnetospheric Currents to S_q. J. Pure and Applied Geophysics, March 1988.

Response of Magnetotail Magnetic Field Topology to Changes in the North-South Component of the Interplanetary Magnetic Field. Presented to the American Geophysical Union Meeting, Baltimore MD, May 1988.

A Time Dependent, Source Driven Magnetospheric Magnetic Field Model. Presented to the American Geophysical Union Meeting, Baltimore MD, May 1988.

Prediction of Plasma Parameters in the Low-Latitude Boundary layer and Plasma Sheet Using Gradient Drift Entry, Presented to the Fall American Geophysical Union Meeting, San Fransisco, CA, December 1987.

Variation of Plasma Velocity Distribution Functions Across the Low-latitude Boundary Layer Driven by the Gradient Entry Process. Presented to the International Union of Geophysics and Geodesy, Vancouver British Columbia, August 1987.

The Topology of Currents Flowing Into and Out of the Ionosphere. Presented to the International Union of Geophysics and Geodesy, Vancouver British Columbia, August 1987.

The Entry of Magnetic Waves Into the Magnetosphere and their effect on the Plasma sheet. Presented to the International Union of Geophysics and Geodesy, Vancouver British Columbia, August 1987.

Prediction of Plasma Parameters in the Low-latitude Boundary Layer and Plasma Sheet Using Gradient Drift Entry Theory. Presented to the American Geophysical Union Meeting, San Fransisco, December 1987.

Use of Geosynchronous Magnetometer Measurements to Estimate Solar Wind Parameters. Presented to the American Geophysical Union Meeting, San Fransisco, December 1987.